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THE DEVELOPMENT OF THE CRYOTEL™ FAMILY OF COOLERS

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ABSTRACT

This paper focuses on the design and development of the CryoTel™ family of cryocoolers, which currently consists of the CryoTel™ CT and the CryoTel™ MT. The CryoTel™ is based on Sunpower's M77 and M87 cryocoolers with design enhancements to allow for operation in applications with ambient operating temperatures that range from $-40\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$. The CryoTel™ is a linear free piston integral Stirling cryocooler that makes use of gas bearing technology for non-contact operation and a Digital Signal Processor (DSP) based controller with closed-loop temperature control. The CryoTel™ and controller can be configured to operate across a wide range of input voltages including 24 Vdc to 240 Vac.

The CryoTel™ CT weighs 2.7 kg and has a cooling capacity of up to 11 W @ 77 K with 160 W of input power. The CryoTel™ MT has a cooling capacity greater than 5.0 W at 77 K with 80 W of input power and weighs 1.65 kg.

These cryocoolers can be modulated and operate efficiently over a wide range of heat loads and ambient conditions. Test results for both coolers across the range of operating conditions are reported.

INTRODUCTION

Sunpower started the development of small scale Stirling coolers in the early 1990's with the introduction of the M223 and the M77 [1]. The M223 was designed to lift 45 W from $-50\text{ }^{\circ}\text{C}$ to room ambient so that it could provide active cooling for high speed microprocessors. A version of the M223 is currently being developed to cool fresh food. The M77 was designed to operate at cryogenic temperatures with a cooling capacity of 4 W @ 77 K. Both coolers share the same motor/piston components with the "front end" optimized to serve the specific application. The M77 and M223 are linear free piston integral Stirling coolers where the piston and displacer are arranged in an in-line configuration as shown in FIGURE 1.

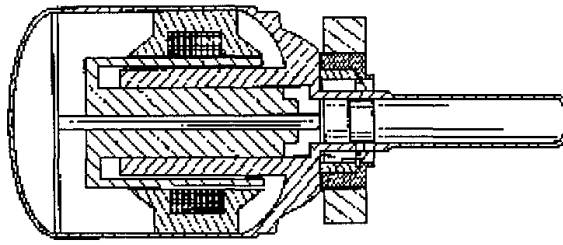


FIGURE 1: Schematic configuration of a linear free piston integral Cryocooler.

The M77 has been in limited production at Sunpower for the last ten years. It is built in small lots by highly trained personnel and has been delivered to various customers including NASA, which qualified it to fly on the RHESSI solar orbiter mission. The M77 has been operating on RHESSI since February of 2002.

In 1998, In-X, a medical products startup company invented a product that could liquefy oxygen in the homes of patients who require liquid oxygen therapy. The company approached Sunpower with a need for a small, highly efficient, low cost cryocooler that could provide cooling capacity of greater than 9 W at 87 K with 155 W of input power. The M87 [2], based on the M77, was developed for this customer's application.

The two primary goals of the M87 design were to increase the available cooling power and to have a cooler design that could be mass produced [3] at low cost in a factory set-up, rather than by highly trained and experienced technicians. The result of this effort was a cooler with about half the number of components and welded or brazed joints as the M77. The cooling capability of the M87 is 7.5 W @ 77 K with 150 W of input power. The substantial reduction in the number of parts and a design that aimed toward mass production without compromising performance proved itself feasible and successful.

When the cold end of the M87 reaches liquid oxygen temperature, the heat load on the cryocooler increases dramatically as the oxygen changes from a gas to a liquid. As long as there is enough gaseous oxygen available at the cold end, the liquefaction of oxygen forces the cooler to operate at a known and narrow temperature span. For the liquid oxygen application to have the best yield, the M87 is always installed with the cold tip down. The M87, while being a leap forward in the design for manufacturing, is intended to operate in a controlled environment for a specific application and at a known orientation. It lacks the capabilities required to answer the needs of telecommunication and industrial applications. In these environments the cooler has to operate over a wide range of ambient temperatures, in different configurations and physical orientations. In addition, the cooler has to be capable of operating from DC or AC power sources and to have the ability to be precisely controlled and monitored.

The lessons learned from the M77 and M87 programs and the requirements imposed by the telecommunication and industrial applications combined to serve as the starting point for the development of the CryoTel™ cryocoolers.

DESIGN & SIMULATIONS

The initial specifications for the CryoTel CT were set as follows:

Cooling Power: >5.5 W @ 60 K

Input power: 200 We (max)

Operating ambient: -40 °C to +60 °C

Power Supply: 24 Vdc
Controller: Close Loop Temperature Controller
Temperature Stability: +/-0.1 K

Configuration

The CryoTel is an integral free piston linear Cryocooler. The piston and displacer are mounted along the same axis. The piston is designed to operate at the center of a moving permanent magnet linear motor [4]. The CryoTel is a true free piston machine in which the piston is not axially constrained by mechanical means. Such a configuration simplifies the mechanical arrangement, which manifests itself in ease of assembly and reduction of potential side loads. When at rest, the piston can be anywhere along its cylinder. Through the application of a start-up sequence [5] by the controller and the linear motor, the piston is moved to the vicinity of the pneumatic dynamic centering system.

After the centering sequence is complete, the controller then drives an oscillating current waveform into the linear motor. The force from the linear motor creates the sinusoidal motion of the piston. The displacer is driven by the pressure wave in the compression space acting on the area of its rod. The rod extends through the center of the piston into the bounce space and is attached to a planar spring [6]. Both the piston and displacer are supported by gas bearing systems to provide non-contact operation between the moving parts of the cryocooler.

The controller is DSP based and uses reconstruction [7] to measure and control the piston amplitude. The CryoTel controller provides closed loop temperature control with an accuracy of +/-0.1 K. The controller also utilizes a serial communication port for monitoring and setting variables such as cold end temperature.

Simulations

To simulate the performance of the cooler under various conditions, several methods and codes were used. SAGE [8] was used as the main computer simulation to predict the thermodynamic cycle of the design. Sunpower internal analysis codes were also used. It should be noted that all of these simulations are continuously compared and evaluated against the hardware being built and tested to allow refinement and adjustment of the different coefficients, thus improving the accuracy of the simulations.

Motor

For a cryocooler with a fixed piston amplitude, the input power increases as the cold end temperature decreases. To maintain an acceptable level of motor efficiency while allowing for a small cooler, the piston dimensions were optimized to reduce the diameter and increase the stroke. In this way the swept volume is maintained while the increase in piston velocity reduces the force required from the motor.

The windings of the linear motor are made in the shape of a simple bobbin nested inside the outer lamination assembly. The inner laminations are mounted on and carried by the outside diameter of the cylinder. The permanent magnet segments are arranged to form a cylinder on a structure of non-magnetic material [9] that moves in the air gap between the outer and inner laminations.

Gas Bearings

The CryoTel designs utilize gas bearing systems between all of the moving parts. Since the applications call for operation in any orientation and over a wide range of ambient conditions, the gas bearing systems were enhanced and modified for greater support. The gas bearing systems are energized by capturing and storing the high peak of the pressure oscillation in the cooler's compression space [10]. That gas then flows through pneumatic metering systems into and through the clearance seal areas to provide the force necessary to prevent contact.

Materials

Special attention was given to the selection of the materials for the main components due to the requirement for the coolers to withstand the wide range of operating temperatures. Wherever possible, identical materials were selected to form the clearance seal pairs. In this way, minimal changes of critical dimensions were ensured. The use of plastic materials and polymers was minimized and scrutinized for low out-gassing rates. The gas containment structure of the CryoTel coolers is hermetically sealed and made of stainless steel in combination with materials with good thermal conduction, such as copper, at the heat exchanger [11] zones.

Driver/Controller

The CryoTel controller applies a 60 Hz, modified square wave voltage waveform to the winding of the linear motor. The modified square wave driver has advantages over both a simple square wave driver and a sinusoidal pulse-width-modulated (PWM) driver. With the modified square wave, the lower order harmonics inherent to the simple square wave can be eliminated. This lowers the ripple in the current waveform and reduces losses in the motor. Unlike the sinusoidal PWM drive, the modified square wave drive has no measurable switching losses, resulting in a highly efficient controller.

The controller uses a platinum RTD or a cryogenic silicon diode to sense and control cold end temperature by modulating the stroke of the piston. The controller can maintain the cold end temperature to within +/- 0.1 K across a wide range of operating conditions. The controller also has a serial interface that allows it to communicate relevant cooler data to the outside world. The CryoTel CT and MT currently use the same controller hardware with slightly different software to account for the differences in the motor and overall performance. The controller dimensions are L 124 mm x W 84 mm x H 38 mm and it can operate from -40 °C to +60 °C ambient temperature with cooling by free convection.

Manufacturing Capabilities

Throughout the development program of the CryoTel™ cryocoolers, a strong emphasis was placed on design for manufacturing. A strategic alliance with LG Electronics was formed to enhance our capabilities for mass production and distribution worldwide. A team of LGE engineers and technicians was assigned to work closely with the Sunpower team. While the manufacturing facility at Sunpower is capable of production at the rate of 1000 coolers/month the needs for the telecommunication applications as anticipated worldwide is many times over. A reliability testing program has been set and is currently under way at the facilities of LGE in South Korea.

TEST RESULTS

Both the CryoTel CT and MT perform within 95% of the levels predicted by the design simulation tools. FIGURE 2 is a graph of the CryoTel CT cooling capacity and efficiency at various input power levels using sine wave driver and 37 °C reject temperature.

It should be noted that peak efficiency decreases and shifts to a lower temperature with increased input power. Conduction losses and diminishing thermal properties are the main reasons for decreasing efficiency in the low temperature regime. High heat flux and flow losses in the heat exchangers are the main reasons for decreasing efficiency at high temperature and high lift.

The CryoTel was then tested at different ambient temperatures ranging from -40 °C to +70 °C. These tests were conducted at a constant input power of 160 We. The cooler was mounted in a horizontal orientation and heat was rejected through the use of a fan. Fin base temperature (reject) was measured to be 15 °C above ambient. The plots in FIGURE 3 show the results of those tests.

FIGURE 4 is a performance map for the CryoTel MT. The MT is intended for applications that require lower cooling capacities and a smaller footprint than the CryoTel CT.

The CryoTel MT design uses the technology and configuration developed initially for the CryoTel CT. An innovative heat exchanger [12] was developed and incorporated into the cooler that simplifies production even further. The CryoTel MT retains the high power density and efficiency demonstrated through the CryoTel CT and is a good example of the scaling capabilities of the basic technology. TABLE 1 summarizes the features and performance of the two designs.

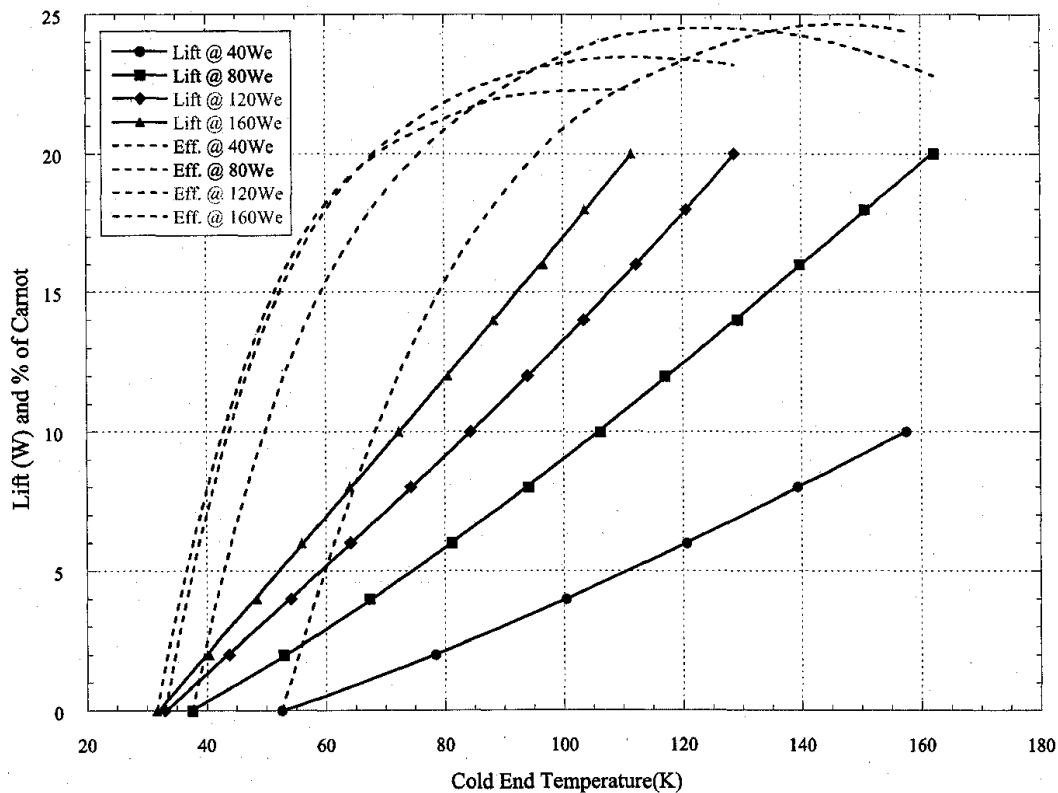


FIGURE 2: CryoTel CT Performance Map. CryoTel CT cooling capacity and efficiency. Reject Temperature: 37 °C.

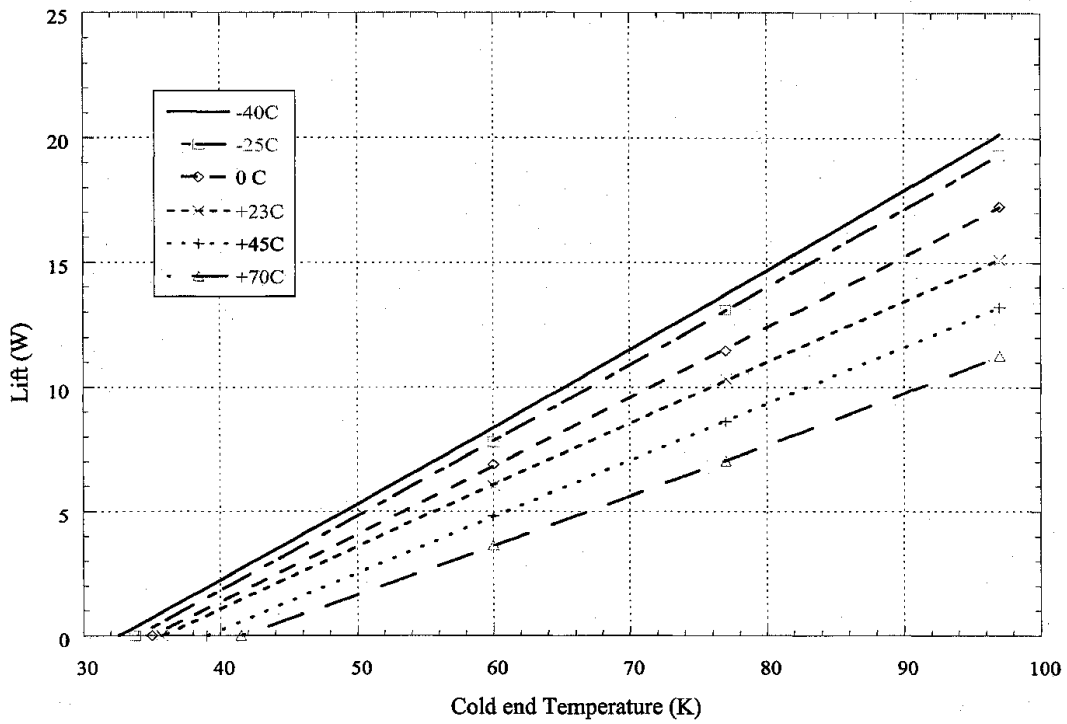


FIGURE 3: CryoTel CT under test at different ambient temperatures.

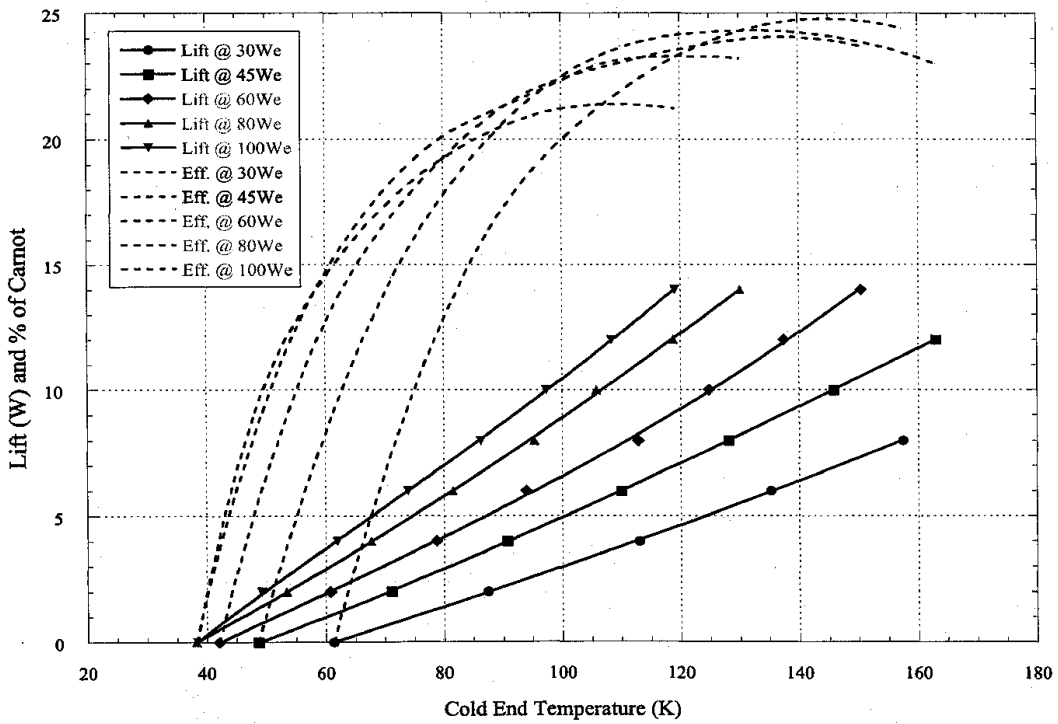


FIGURE 4: CryoTel MT Performance Map. CryoTel MT Cooling Capability and Efficiency. Reject Temperature: 33 °C.

TABLE 1: Comparison of CryoTel CT and MT Features and Performance.

	CryoTel™ CT	CryoTel™ MT
Cooling Capacity	10.5 W @ 77 K	5 W @ 80 K
Input Power	< 200 We	< 100 We
Operating Ambient (°C)	-40 to +60	-40 to +60
Power Supply	24 Vdc / 120-240 Vac	24 Vdc / 120-240 Vac
Controller Type	DSP Closed Loop Temperature Control	DSP Closed Loop Temperature Control
Temperature Stability	+/- 0.1 K	+/- 0.1 K
Cooler Length	258 mm	218 mm
Cooler Diameter	83 mm	73 mm
Cooler weight	2.7 kg	1.65 kg

CONCLUSION

A new family of cryocooler products has been developed. Both cryocoolers, the CryoTel™ CT and the CryoTel™ MT, are proved to track the simulation and analysis. The design of the coolers utilizes state of the art technology and know-how in combination with robust configurations. These coolers are of a compact size, high power density and high efficiency. A new DSP controller was developed which provides flexibility, adaptability and accuracy. A successful collaboration between LG Electronics of Korea and Sunpower has been formed to bring this family of coolers to the market place.

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